On Board Measurement of Carbon Dioxide Exhaust Car Emissions Using A Mid-Infrared Optical Based Fibre

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***Abstract*—This paper describes the investigation of an optical sensor system for the online measurement of carbon dioxide emissions in the exhaust system of a motor vehicle. Current anti-pollution technology installed in motor vehicles fail to meet monitoring requirements as specified by the European Commission. A robust sensor design and construction have made it suitable for installation on the exhaust of a motor vehicle. Results are presented for the sensor output when calibrated to carbon dioxide supplied from a cylinder at the Centro Ricerche Fiat (CRF) research laboratory initially and in-situ in the exhaust of a Fiat Croma (diesel engine) during full scale tests on a roller test bench also at CRF.**

I. INTRODUCTION

The modern automobile operates on the rapid oxidation (through combustion) of complex hydrocarbons known as diesel fuels and gasoline. During this combustion process a variety of gases are produced such as water vapour (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_X) and oxides of sulfur (SO_X). In addition the internal combustion process also produces smoke and airborne particulate matter [1]. This environmental pollution is of major concern both in local issues such as human health problems, leading to major cost implications, and as a global concern which effects the Earth's environment by processes such as acid precipitation, photochemical smog and climate change.

Although not strictly considered a pollutant, as it already exists as a trace gas in the atmosphere, excessive levels of CO_2 produced by road vehicles are considered a prime contributor to climate change known as the "Greenhouse Effect". Although globally the majority of atmospheric CO_2 generated is due to industrial processing and manufacturing plants, in urban areas the private car is the single greatest contributor to increased levels of CO_2 and other gases such as carbon monoxide, oxides of nitrogen, and hydrocarbons present in the atmosphere [2]. To increase the quality of air, the EU have introduced a succession of increasingly stringent automotive emission legislation over the past decade or so [3].

Currently, no exhaust gas sensor has been developed which can be used for online measurements of CO_2 present in the exhaust of an engine. The Lambda sensor merely measures the oxygen content in the exhaust and signals to the engine management system whether too much or too little fuel is being burnt [4]. Another known issue with the Lambda sensor is that it degrades over time on contact with hot and corrosive elements in the exhaust. The net effect of this decline is that eventually the Lambda sensor may produce false readings, which either causes extra fuel to be burnt or not enough. This reduces fuel economy and can ultimately damage the catalytic converter, and is also responsible for the production of increased levels of pollution. As a result of this the Lambda sensor must be replaced every 30,000 to 50,000 miles, which is much less than the lifetime of an average vehicle [5].

Clearly, an automotive gas sensor needs to be developed, which is capable of quantifying the levels of CO_2 and other gases entering the atmosphere from an engine and which is immune to corrosion by the agents present in the exhaust. An optical fibre gas sensor is ideally suited to this task as it is constructed from glass and ceramic components. In addition to this by developing an optical fibre sensor based on infrared absorption spectroscopy, a sensor for a particular gas can be developed which is not cross sensitive to the presence of other gaseous species in the exhaust [6].

Various detection schemes for gases such as methane [7] and oxygen [8] using optical fibre sensors operating in the near-infrared region of the electromagnetic spectrum have been reported in the literature. In addition to this mid-infrared optical fibre sensors have been developed for the detection of hydrocarbons [9] and ethyl chloride [10]. However none of these schemes are suitable for use in a vehicle as they consist of bulky and expensive lasers and spectrometers suitable only for use in remote monitoring of industrial plants.

II. THEORY

A. Absorption Theory

Every molecular species absorbs light at different wavelengths; therefore for each molecule we have a unique absorption spectrum. CO_2 absorbs light at various wavelengths across the infrared region. This absorption spectra has been published previously [11] and is shown in fig. 1. CO_2 has a characteristically strong absorption band extending from 4.2 μm to 4.5 μm with high peaks visible at 4.23 μm and 4.28 μm. This absorption band has significantly greater absorption cross section than the corresponding near-infrared overtones at 2.7 μm.

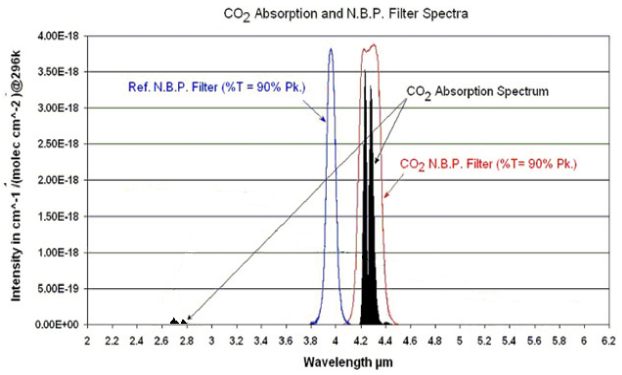

Fig. 1. CO_2 absorption spectrum and filter cutoff wavelengths.

Numerous gas species exist in the exhaust of an automobile as was discussed in section 1. Each of these species could have the potential to cause cross sensitivity reducing the effective use of the sensor. Therefore during initial development of the sensor the absorption spectra of H_2O, CO, NO_2, NO and SO_2 were examined. The results showed that there was absorption due to these gases evident across several wavelengths within the infrared region. However no significant absorption due to any of these gases was found to exist between the wavelengths 3.8 μm and 4.5 μm. Therefore the use of narrow bandpass filters on both the reference and CO_2 detectors, with pass bands of 3.905 μm to 3.995 μm and 4.14 μm to 4.32 μm respectively, will ensure that the sensor is not cross-sensitive to any gaseous species present in the exhaust.

B. Concentration Determination

The Beer-Lambert law defines the relationship between absorbance and concentration of an absorbing species and is shown in equation 1.

$$\frac{I}{I_O} = e^{(-\varepsilon cl)} \quad (1)$$

Where I is the transmitted intensity, I_O is the incident intensity, l (cm) is the optical path length (37 mm), c (cm^{-3}*Mol) is the concentration of the species and ε (cm^2/Mol) is the molar absorbtivity of the species. A variation of the Beer-Lambert Law can be used to calculate the concentration of the gases present.

$$ppm = \frac{-\left[\ln \frac{I}{I_0}\right]\left[w \times d \times 10^{6}\right]}{\sigma \times N_A \times l} \quad (2)$$

Where σ (cm^2/Molecule) is the absorption cross section, w (Kg/Mol) is the molecular weight of the species, d (Kg/m^3) is the density of the species, NA is Avogadro's constant and ppm ($Kg*g/m^6$) is the gas concentration in parts per million.

III. EXPERIMENTAL SET-UP

The optical fibre sensor, as assembled in the laboratory and the experimental measurement setup are shown schematically in figure 2. Infrared radiation in the wavelengths range between 2 µm and 8 µm was input into the gas chamber via an optical fibre (500/550 0.5 m core/clad diameter chalcogenide, part of a fibre bundle containing three other identical fibres) from a filament emitter. The emitter, a NL5LNC pulsable (0.5–10 Hz) nichrome filament from Ion Optics, was coupled to the fibre using a custom-made PTFE connector. The pulsed infrared radiation from the emitter was launched from the transmitting fibre into the measurement chamber using the calcium fluoride (CaF2) collimating lens.

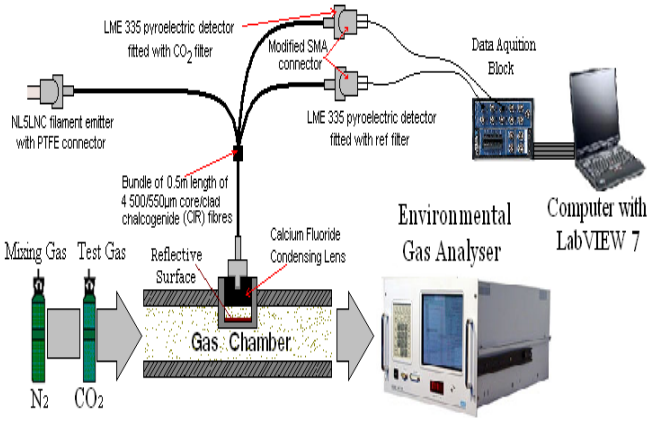

Fig. 2. Mid-infrared optical fibre CO2 sensor.

Following transmission through the 18.5mm length gas chamber, the infrared radiation was reflected from an end facing perpindicular alumnium surface. The infrared light signal is returned into the receiving optical fibre collimating lens where it is condensed. The modulated radiation was guided to the LME 335 detector (fitted with a narrow bandpass filter, as discussed in section II.) via a seperate fibre from the optical fibre bundle. The output of the fibre bundle was connected to the pyroelectric detector using a modified SMA connector. A second LME 335 detector (fitted with a narrow bandpass filter, as discussed in section II) was attached to another fibre in the bundle and used as a reference channel. The output voltage of the pyroelectric detectors was captured on a PC using the National Instruments PCI 6013 DAQ card and LabVIEW software.

Test gas was used from a bank of cylinders consisting of CO_2 and zero grade Nitrogen. These gases were mixed during the testing stages with the flow of gas from each cylinder to the gas chamber being controlled using standard mass flow controllers. Conventional piping was used to transport the gas mixture to and from the test gas chamber fitted with the optical sensor. The concentration of CO_2 present in the gas chamber was also monitored simultaneously using commercial gas analyser (Advance Optima process gas analyser from ABB).

IV. Calibration

Calibration of the sensor using the commercial gas analyser was required in order for the sensor to be capable of producing accurate concentration readings. In order to achieve this laboratory based experiments were carried out using the experimental set-up described in section III. The CO_2 gas was input at a constant concentration and the commercial analyser accurately recorded the concentration of the gas under test.

$$\sigma = \frac{-\left[\ln \frac{I}{I_0}\right]\left[w \times d \times 10^{6}\right]}{ppm \times N_A \times l} \qquad (3)$$

The signal strength received from each of the pyroelectric detectors was recorded before and after the gas was allowed into the gas chamber. A variation of equation 2 shown in equation 3 was utilised to calculate the measured absorption cross section for CO_2. This measured absorption cross section represents the average absorption cross section for CO_2 covered by the narrow bandpass filter visible from 4.23 μm and 4.28 μm. This value was used during further tests to calculate the concentrations of CO_2 present in the test gas chamber.

V. Results And Discussions

A. Cold Gas Tests

Further experimental tests were carried out to examine the functionality of the sensing system under development using cylinder gases in a lab environment in Centro Ricerche Fiat, Italy. The LabVIEW program was initiated and the commercial gas analyser was turned on. The Concentrations were diluted using a bank of N_2 every few minutes while the commercial gas analyser recorded concentrations in the gas chamber. The date recorded from the pyroelectric detector were utilized in equation 2 along with the measured absorption cross section to calculate the concentrations present in the gas chamber. These were compared to the commercial analyser's concentrations as shown in fig. 3.

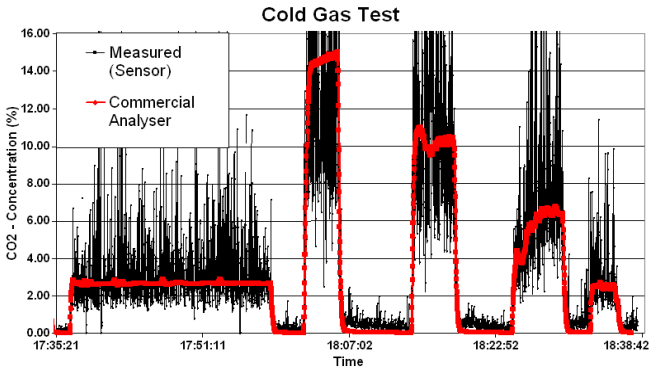

Fig. 3. Shown is the response from the sensing system to the initial cold gas test, also shown are the equivalent recordings from the commercial gas analyser.

The "cold gas" test of fig. 3 show that the measured results agreed closely to that of the commercial gas analyser. The optical fibre sensor system has therefore been shown to be accurate in recording the CO_2 concentrations and it has demonstrated fast response times of less than 30 milliseconds.

B. Engine Tests

Further tests were carried out on the exhaust of a Fiat Croma in a test facility at Centro Ricerche Fiat, Italy. The sensing system was integrated into the exhaust system of a Fiat Croma 1.9 liter TCI/DI diesel engine [12]. Both the developed sensor and the commercial analyser were set up to record. A photograph of the setup is shown in fig 4.

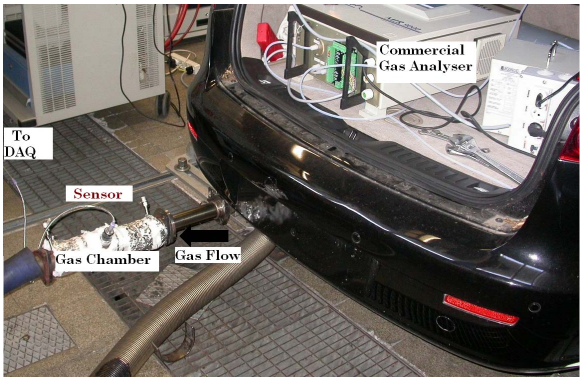

Fig. 4. Photo of the engine test setup carried out in facilities in Centro Ricerche Fiat, Italy.

The engine was started and the car was taken through each of the steps of the European EUDC (Extra Urban Driving Cycle) [13]. The EUDC is part of a driving test cycle used for emission certification of light duty vehicles in Europe. The EUDC stage is used to simulate more aggressive, high speed driving modes. The cycle took approximately 22 minutes to complete and the maximum speed of the EUDC cycle is equivalent to a speed of 120 km/h.

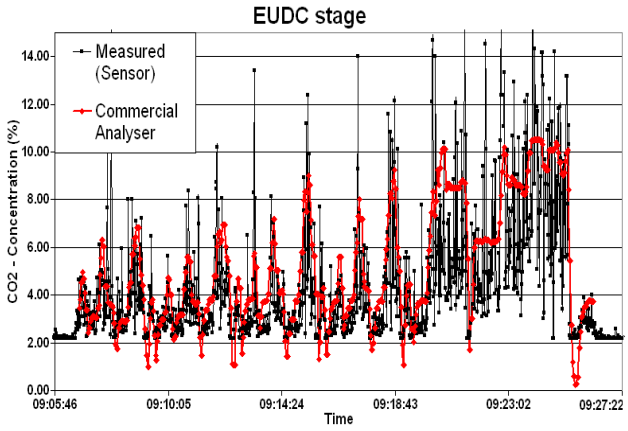

Fig. 5. Measured concentrations from the sensor for the EUDC test cycle on a Fiat Croma engine exhaust. Also shown are the equivalent recorded concentrations from the commercial analyser.

Tests carried out in the exhaust of the Fiat Croma show that the sensing system performed correctly and was capable of operating within the harsh exhaust environment. The sensor faithfully reproduced the concentrations of CO_2 compared to that simultaneously recorded on the commercial gas analyser for the whole duration of the test cycle. The sensor has also demonstrated operation over a wide range of concentrations (2% – 15% CO_2) and a limit of detection smaller than that present in a modern automobile. Previous testing using a similar sensor showed that the detection and transmission systems are capable of operating over long periods of time [14]. Further testing is necessary to assess whether if the optical fibre sensor would be capable of reliably detecting CO_2 over a prolonged period of a time when fitted to an automobile during normal operation.

VI. Conclusions and Future Work

An optical fibre sensor for the detection of carbon dioxide in road vehicles has been successfully demonstrated.

This sensor proved to be capable of monitoring concentrations of between 2%-15%, as recorded by the commercial gas analyser and is capable of working in the harsh environment of the exhaust system of a motor vehicle.

Further testing is necessary to assess the ability of if the optical fibre sensor to reliably detect carbon dioxide over a period of time when fitted to a road vehicle. It is also necessary to further assess how the operation of the sensor would be affected by an accumulation of soot particles and presence of water vapour over time.

Future work will involve the permanent installation of the sensor onto a motor vehicle and monitoring the results at different mileage intervals, to the affect on the performance of the sensor in the presence of various environmental factors e.g. harsh road conditions.

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